# SPECIFICATION

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# SELF-ALIGNING ULTRASONIC DISPLACEMENT SENSOR SYSTEM, APPARATUS AND METHOD FOR DETECTING SURFACE VIBRATIONS

## Cross Reference to Related Applications

This application claims the benefit of U.S. Provisional Application No. 60/261,722, filed January 12, 2001.

## Background of Invention

[0001]     This invention relates generally to vibration sensing, and specifically to sensing musical drumhead vibrations using an ultrasonic transducing element.

[0002]     This invention comprises a device that permits sensing of surface vibrations by use of reflected sound at a frequency substantially higher than that of the surface vibrations to be sensed. One important application is for sensing drumhead vibrations of a tunable drum so as to provide a signal to a sound analyzer that displays to the drum's player the note that is being played and the accuracy of its pitch relative to the standard musical scale.

[0003]     Present sensing devices for this purpose utilize electromagnetic, optical, or acoustic methods that operate without contacting the drumhead, or piezoelectric or other methods that require the sensing element to be in physical contact with the drumhead. Each of these methods has its deficiencies insofar as pickup of extraneous signals such as "AC hum" (from electrical environment or from the room lighting) or room ambient sound, requiring use of a separate "target" that must be attached to the

drumhead, direct contact with the drum head, and / or difficult setup and calibration / alignment.

## Summary of Invention

[0004]  Ultrasonic transducing elements are used to measure vibrations of a nearby musical drumhead or other vibrating surface. A first ultrasonic transducer emits an ultrasonic signal and a second ultrasonic transducer listens for an echo of that signal. A *phase change* of the echoed (reflected) signal is compared to a reference signal to create a representation signal which represents the movement of the drumhead or other vibrating surface. For this comparison to be properly made, a deviation signal is generated that defines an average deviation of the reference signal from optimum, which is then used to *self-align* the reference signal to the reflected signal.

[0005]  The disclosed invention is capable of operating at a relatively large distance from the drumhead. It does not contact the drumhead nor does it require a special target to be placed on the drumhead. It does not require any specialized setup, does not contact the drumhead, and is insensitive to interference from room ambient sound, electromagnetic signals, lighting / optical signals, or temperature changes. All of these are significant advantages relative to presently-used vibration sensing methods. Ease of installation is another major advantage. To use the sensor, it is simply fixtured in place with its active elements facing the drumhead. Within a large operating range, the sensor system automatically compensates (self-aligns) for differences in the set operating distance to the drumhead, air temperature, and other variables.

## Brief Description of Drawings

[0006]  The features of the invention believed to be novel are set forth in the appended claims. The invention, however, together with further objects and advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawing(s) in which:

[0007]  Figure 1 is a side plan view illustrating the placement of the ultrasonic transducer relative to a vibrating surface such as a drumhead, and schematically illustrating the emission and reception of ultrasonic signal as well as the vibration of the vibrating surface.

[0008]    Figure 2 is a block diagram of the circuit disclosed herein for processing the transducer signals to sense the vibration of the surface and for self-aligning the overall system.

[0009]    Figure 3 illustrates the signals at various junctures of the circuit of Fig. 2, when the drumhead or similar surface is quiescent (not vibrating), and when the system is optimally aligned / calibrated. Figure 4 illustrates the signals at various junctures of the circuit of Fig. 2, when the drumhead or similar surface is quiescent (not vibrating), but when the system moves out of optimum alignment / calibration. As also illustrated by Fig. 4, the detection that the system is out of alignment / calibration is used as the basis for self-aligning the system back into the proper calibration, and is used to self-calibrate the system during its initial setup.

[0010]    Figure 5 illustrates the signals at various junctures of the circuit of Fig. 2, when the drumhead or similar surface is vibrating.

[0011]    Figure 6 illustrates how the various signals in Fig. 5 are used to detect the vibrational movement of the vibrating surface, which serves as the basis for displaying information pertaining the said vibrational movement.

## Detailed Description

[0012]    The Ultrasonic Displacement Sensor is a device that detects the motion of a vibrating surface, such as but not limited to a drumhead, toward or away from the sensor itself. For sensing timpani drumhead or other tunable instrument vibrations such as is described in commonly-assigned and invented U.S. Patent 4,741,242, a range of interest is about 20 to 1000 Hz, which in this disclosure will be characterized generally as vibrational frequencies in the range of less than approximately 1 kHz. For sensing vibrations of other surfaces or objects, it is understood that different ranges of vibrational frequency may be of interest.

[0013]    For sensing drumhead vibrations, the sensor consists of two ultrasonic transducers operating at about 40 kHz, which, in particular, thus operate at a frequency about 40 times higher than the highest vibrational frequency of interest to be detected from the drumhead. One of these ultrasonic transducers emits the 40 kHz tone, and the second listens for an echo from the drumhead. For sensing vibrations

generally, the ultrasonic transducers utilized should operate at a frequency substantially higher (e.g., optimally at least 40 times as high, preferably as high as possible without limitation consistent with transducer technology and cost, but at least 10 to 20 times as high) than the highest vibrational frequency of interest for detection. With this general understanding that the optimum transducer frequency will depend on the upper range of the vibrational frequencies of interest, the ultrasonic transducers used in this disclosure for purposes of illustration will be characterized as operating at approximately 40 kHz.

[0014]    In a preferred embodiment illustrated in Figure 1, the emitting *11* and receiving *12* transducers are located approximately 2 inches (i.e. 5 cm) away from the vibrating surface *13* such as a drumhead, and are preferably angled and set to focus on a substantially single spot (as focused a beam as possible is preferred consistent with available transducer technology and cost, but is not required) approximately the same 2 inch (5 cm.) distance as the drum head. This maximizes the reflected signal from this one point, and thereby diminishes the contribution of any other reflection, in essence focusing the sensing to a smaller spot. Vibrating surface *13* is illustrated in a "o" quiescent position, as well as in a "+" position at the highest point of its vibration and a "–" position at the lowest point of its vibration. The ultrasonic emissions *14* are illustrated to be operating at approximately 40 kHz (i.e., spaced from one another by ~ 1/40,000 sec), and the vibrations *15* of vibrating surface *13* (e.g., the drumhead) from high point + to low point are illustrated to be in the range of less than approximately 1 kHz (i.e., vibrating with a cycle time > ~ 1/1000 sec).

[0015]    Although these sensors in the preferred embodiment are located approximately 2 inches (5 cm.) away and angled as described above so that their centerlines meet at a point about 2 inches (5 cm.) away from the transducer face, and the nominal setup of the pickup is then 2 inches (5 cm.) from the head, they are capable of being placed approximately eight inches (20 cm), one foot (30 cm), or even three or more feet (approximately 1 or more meters) away. They can also be placed less than an inch (2.5 cm.) and even as close as about 1/4 inch (approximately 5mm) away and still maintain an effective signal. Additionally, the converging of the transducer centerlines at the vibrating surface is preferred, but not a necessary feature.

[0016]    The sensors are placed proximate the vibrating surface *13*, e.g., drumhead as described above, with their active elements facing the drumhead, either outside the drum as illustrated in, e.g., Fig. 7 of U.S. 4,741,242, or inside the drum so as to be hidden from view. The stronger the reflected signal is, the less chance there is for a false reflection to influence the signal. Thus, any setup which optimizes the strength of the reflected signal is preferred.

[0017]

It is the *change in phase* of the returned 40 kHz echo that is measured to determine the movement of the drumhead or other vibrating surface *13*. As illustrated in Figure 2, the phase of the reflected signal *202* received by receiving transducer *12* and emerging from amplifier *204* is compared to a reference signal *206* originating from and driven by a timing signal from oscillator *208* using a comparator (e.g. exclusive OR) circuit *210* to generate comparison signal *214*. Comparison signal *214* is then passed through a low pass filter *212* which only passes through frequencies below a low pass threshold of approximately 1 kHz (and more generally, below the highest vibrational frequency of interest) to create a representation signal *216* which represents the movement of the vibrating surface. Amplified *230* output from oscillator *208* also drives emitting transducer *11*. (The exclusive OR circuit *210* illustrated as an example drives its output high when both inputs are high and also when both inputs are low, and it drives its output low when one input is high while the other input is low. It is understood that an exclusive OR inverse to this is also feasible within the scope of this disclosure and its associated claims.) For the exclusive OR comparator *210* to work properly, the phase of the reference signal *206* must be adjusted so that it is optimum when the vibrating surface is at its center (non-displaced, equilibrium) "o" point. This is accomplished by using a second, "low-low" pass filter *218* with cutoff frequency at 1 Hz (and generally, substantially below the lowest vibrational frequency of interest) to generate a deviation signal *220* that defines the average deviation of the reference signal *206* from optimum. This deviation signal *220* is used in combination with gating logic *222*, an up/down counter *224* (with illustrated up input *232* and down input *234)* and a delay device *226* such as a shift register, to *self-align* (i.e. self-calibrate) the reference signal *206* originating from oscillator *208* relative to the reflected signal *202*, prior to their being compared with exclusive OR circuit *210*. This is done by stepping counter *224* up or

down as required to select the correct delay via delay device *226* and thereby provide optimal sensitivity. While Figure 2 illustrates deviation signal *220* being derived directly from representation signal *216* and *indirectly* from comparison signal *214* with low pass filter *212* and low-low pass filter *218* in series, it is understood that deviation signal *220* may also be derived *directly* from comparison signal *214* by placing low pass filter *212* and low-low pass filter *218* in parallel with one another. The key point is that deviation signal *220* is in any event derived from comparison signal *214*, whether directly without low pass filter *212* intervening, or indirectly as illustrated in Fig. 2 with low pass filter *212* intervening. Thus, in general terms, whether directly or indirectly, deviation signal *220* is extracted by passing through from comparison signal *214*, frequencies lower than the low-low pass threshold established by low-low pass filter *218*.

[0018]    Representation signal *216*, which represents the actual vibrational movement of vibrating surface *13*, may then be provided to a vibrational information display device *228* in order to provide human-readable information about this vibrational movement. Display device *228* can present this information in any form that is suitable to the application. For drumhead vibration, vibrational information display device *228* may, for example, comprise vibrational display means for displaying the note sounded and its pitch relative to a preset standard so as to indicate to the player whether or not the drum is set to the desired pitch, such as the display device disclosed and claimed in commonly-owned and invented U.S. Patent 4,589,324. The display device disclosed and claimed in U.S. 4,589,324 displays one of the alphabetic characters A, B, C, D, E, F and G representing a musical note corresponding with said vibration of said surface *13*; a musical sharp note indicator if said musical note is sharp; a musical flat note indicator if said musical note is flat; and a degree to which said musical note is out of tune using an out-of-tune indicator such as a plurality of spaced-apart strobe bar indicators.

[0019]    To further illustrate the inherent operational properties of the circuit disclosed in Figure 2, Figures 3 through 6 illustrate reference signal *206*, reflected signal *202*, comparison signal *214*, representation signal *216*, and deviation signal *220*, produced by this circuit, in various operational situations. Reference signal *206*, reflected signal *202*, and comparison signal *214* are represented as "square" waves

simply for simplicity.

[0020]    Figure 3 illustrates all of the reference signal *206* , reflected signal *202* ,
comparison signal *214* , representation signal *216* , and deviation signal *220*
inherently produced by the circuit of Fig. 2, when the drumhead or similar surface is
quiescent (not vibrating), and when the system is optimally aligned / calibrated. As
noted earlier, the phase of the reference signal *206* must be adjusted so that it is
optimum when the vibrating surface is at its center (non-displaced, equilibrium) "o"
point. In detailed operational terms, this means that it is desired to maintain the
phase of reference signal *206* one-quarter of a cycle ahead of the phase of reflected
signal *202* , as shown in Fig. 3. By maintaining a quarter-cycle separation between
reference signal *206* and reflected signal *202,* comparison signal *214* emerging from
exclusive OR comparator circuit *210* cyclically runs high (+) half the time and low (-)
half the time at twice the transducer frequency. Most importantly, this means that the
*average* value of comparison signal *214* will be quiescent (o), when averaged over any
time frame substantially larger than the time frame of a single transducer cycle. Thus,
when comparison signal *214* , which has an 80 kHz frequency, is run through the 1
kHz low pass filter *212* , representation signal *216* will be flat, and it will also be
centered at the quiescent (o) amplitude. This is precisely what is desired, because 1)
the drumhead is quiescent and so the representation signal *216* representing its
movement should also show quiescence, and 2) the system is calibrated about the "o"
point. Deviation signal *220* emerging from low-low pass filter *218* is also flat and
centered at the quiescent (o) amplitude, designating proper calibration for reasons to
be discussed further below.

[0021]    Figure 4 illustrates all of the reference signal *206* , reflected signal *202* ,
comparison signal *214* , representation signal *216* , and deviation signal *220*
inherently produced by the circuit of Fig. 2, when the drumhead or similar surface is
quiescent (not vibrating), but *when the system moves out of optimum alignment /*
*calibration* . The detection that the system is out of alignment / calibration is used as
the basis for self-aligning the system back into the proper calibration during
operation, and is also used to self-calibrate the system during its initial setup. In the
illustration of Figure 4, it is assumed that for some reason, the distance between the
drumhead *13* and the transducers *11* and *12* is suddenly, slightly reduced. Such a

reduced distance implies that reflected signal *202* will return to receiving transducer *12* slightly sooner than it would have returned before this sudden reduction in distance. This is represented by the fact that in Figure 4 the second "-" region of reflected signal *202* has been drawn so as to of a slightly shorter temporal duration (by a 5/6 factor) than any of the other + or regions of reflected signal *202*, as may be observed by a careful perusal of Figure 4. Because of this shift, comparison signal *214* emerging from exclusive OR circuit *210* changes after its third + pulse, and it now spends approximately 2/3 of its time in the + state and 1/3 of its time in the state. As a consequence, the *average* value of comparison signal *214* is now 2/3 of the way toward the + state and away from the state. This average value is captured in a rise in the representation signal *216* emerging from low pass filter *212*, again, because low pass filter *212* cuts off frequencies at a frequency substantially below the transducer frequency (1 kHz cutoff compared to 40 kHz transducers for the illustrated embodiments). Deviation signal *220* will also rise over time to be 2/3 of the way toward the + state and away from the state. However, since deviation signal *220* emerges from low-low pass filter *218* which has a 1 Hz (i.e. 1 cycle per second) cutoff in this particular embodiment and a cutoff below all vibrational frequencies of interest generally, it will take much more time for low-low pass filter *218* to fully respond to this rise, and in particular, it will take on the order of one to several seconds to respond. This is illustrated by the upward-sloping portion of the bottom-most representation of deviation signal *220*, which is drawn to a much larger (~ 1 second) time scale than the remainder of Fig. 4.

[0022]

Referring again to Figure 2, it is deviation signal *220* that feeds in to gating logic *222*, up/down counter *224* and delay device *226* to *self-align* (i.e. self-calibrate) the reference signal *206* originating from oscillator *208* relative to the reflected signal *202*. In particular, gating logic *222*, up/down counter *224* provide shift calculation means for determining how much and in which direction the timing signal from oscillator *208* needs to be temporally shifted in order to get back into proper phase with reflected signal *202*, and delay device *226* provides means for actually advancing or delaying (shifting) the provision of timing signal from oscillator *208* to comparator circuit *210* as reference signal *206*. Thus, once deviation signal *220* strays from the central "o" quiescent state, gating logic *222*, up/down counter *224*

and delay device *226* provide one embodiment of a combined self-calibration / self-adjustment means for recalibrating reference signal *206* back into the optimally aligned / calibrated phase of Figure 3, relative to reflected signal *202* . This recalibration is illustrated by the downward-sloping portion of the bottom-most representation of deviation signal *220* in Fig. 4. Once the recalibration is completed, deviation signal *220* returns to its central "o" quiescent state of Fig. 3. In light of this, it is apparent that Figure 3 defines the proper "objective" for calibration.

[0023]      At this point, we can return to examine more closely the original assumption underlying Figure 4, namely, that "for some reason, the distance between the drumhead *13* and the transducers *11* and *12* is suddenly, slightly reduced." This sudden reduction (or likewise an enlargement), in practice, can result from actual physical movement, or from other factors in the external environment such as a change in temperature. When this system is set up initially for a given detection, this eliminates the need to be concerned about the exact distance between the transducers *11* and *12* and the vibrating surface *13* , because this self-aligning / calibrating feature, no matter what the variation in distance, will 1) generate a deviation signal *220* such as in Figure 4 showing how far the system is out of alignment, and 2) recalibrate back toward the proper calibration of Figure 3 by shifting reference signal *206* accordingly via the self-adjustment / calibration means comprising, in this embodiment, gating logic *222,* up/down counter *224* and delay device *226* . Calibration is automatic (self-aligning), and thus setup is extremely simplified.

[0024]      This self-aligning feature allows the sensorautomatically work properly over a wide range of setup dimensions and allows it to continue to operate properly even subject to changing air temperature and other factors, and without placing any special, separate "target" on the drumhead.

[0025]

     Figure 5 illustrates the reference signal *206* , reflected signal *202* , comparison signal *214* , and representation signal *216* inherently produced by the circuit of Figure 2, when the drumhead or similar surface is vibrating, and assuming proper calibration in accordance with the discussion of Figure 4. In this discussion, it is assumed that vibrating surface *13* (e.g., the drumhead) is vibrating at a frequency of 1 kHz or less,

i.e., at a cycle time of 1 cycle per 1/1000 second or longer, as illustrated toward the right-hand side of Figure 1. For sake of discussion, we shall assume that the drumhead vibrates at .5 kHz, that it moves from "o" to "+" to "o" to "-" and back to "+" every 1/500 second. Since the transducer is operating at 40 kHz, i.e., at 80 times this frequency of the drumhead, it can also be assumed that when the drumhead peaks at "+" and is thus closest to the transducer, valleys as "-" and is thus farthest from the transducer, or is moving through "o" at the quiescent position, the drumhead may be approximated as substantially stationary over several transducer cycles.

[0026]

In Fig. 5, the upper triplet of signals designated by "o," shows the drumhead ( *13* ) at "o" over the several transducer cycles for which the "substantially stationary at o" approximation is accurate. As discussed in connection with Figure 3, this means that comparison signal *214* is high half the time and low half the time, and that its *average* value emerging from low pass filter *212* as representation signal *216* will be the quiescent value "o." The middle triplet of signals designated by "+," shows the drumhead ( *13* ) at "+" over the several transducer cycles for which the "substantially stationary at +" approximation is accurate. Here, as discussed in connection with Fig. 4, the closer proximity of drumhead *13* to transducers *11* and *12* will return reflected signal *202* to receiving transducer *12* slightly sooner than occurs when the drumhead *13* is in the "o" position. Thus, comparison signal *214* is higher more of the time and lower less of the time, such that its *average* value emerging from low pass filter *212* as representation signal *216* will be somewhat higher than "o." Finally, the lower triplet of signals designated by "-," shows the drumhead ( *13* ) at "-" over the several transducer cycles for which the "substantially stationary at -" approximation is accurate. In this situation, for all of the reasons discussed before, the *average* value of the comparison signal *214* emerging from low pass filter *212* as representation signal *216* will be somewhat lower than "o." Of course, if one combines the representation signal *216* shown in Figure 5 over several cycles from "o" to "+" to "o" to "-" to "o," and looks at a longer period of time greater than 1/1000 second, it is clear that representation signal will cycle right along with the movement of vibrating surface (e.g., drumhead) *13* , as shown in Figure 6. That is, representation signal *216* , which is an electronic signal inherently generated by the circuitry of Fig. 2, will precisely track and represent the actual vibrational movement *15* of the vibrating surface (e.g.,

drumhead) *13*, as illustrated in Figure 1. Thus, representation signal *216* is an electronic reconstruction from the ultrasonic emission *11* and reception *12*, of the vibrational movement *15* of vibrating surface *13*, which is the desired signal output of the overall system. By feeding representation signal *216* to vibrational information display device *228*, one can then display information about these vibrations to the end user in whatever human-readable manner is desired.

[0027]      Having reviewed Figures 3 through 6, a final comment is in order about the low pass filter *212* and the low-low pass filter *218*. When the vibrating surface *13* is vibrating, it is low pass filter *212* that sifts out the representation signal *216* which is the electronic reconstruction of the vibrational movement *15* of vibrating surface *13*. If the overall calibration should happen to drift high or low away from "o," the center of representation signal *216* will also drift high or low accordingly, but will be masked by the oscillations up to 1 kHz (or whatever magnitude of filtration is set by low pass filter *212*). That is where low-low pass filter *218* comes in, which is 1 Hz for the illustrated embodiment but need not be limited to 1 Hz. Because low-low pass filter *218* filters at a frequency lower than the vibrational frequencies of interest, the frequencies between 1 Hz and 1 kHz will also be masked out, and all that will remain is the center line of representation signal *216*, with its slight upward or downward drift, but without all the 1 Hz to 1 kHz oscillations. This will allow for continuous, automatic recalibration (self-alignment) of the overall system, not only at initial setup, but also throughout operation in response to any and all environmental changes.

[0028]      It is also important to understand that this device, system and method is used to detect *two* types of movement of surface *13*. First, the representation signal *216* emerging from low pass filter *212* represents the detection of the *vibration* of surface *13*, which is generally a form of *periodic* movement, and is the movement that it is ultimately desired to detect and present (e.g., through display device *228*) to the end user. Second, deviation signal *220* emerging from low-low pass filter *218* represents the detection of *gross movement* of surface *13*, which is generally *not periodic*, but rather is generally motion due to gross relative movement between the ultrasonic transducers *11, 12* and surface *13*. This motion is not presented to the end user per se, but is used to self-calibrate the system to ensure accuracy in the presentation of the periodic movement.

[0029]    This sensing system provides significantly more latitude to place the sensor further from the drumhead as noted above, up to three or more feet away -- and eliminates the need to place a special separate "target" on the drumhead itself. This is because the ultrasonic waves are not compromised by ambient light or other radiation, or by ambient sound, and will reflect from a surface whether that surface is optically transparent, translucent, or opaque. Additionally, this system requires very little current, and so can powered by a battery requiring only infrequent recharging or replacement.

[0030]    In essence, the embodiments herein described employ an ultrasonic interferometer for vibration sensing generally and drumhead or tunable instrument vibration sensing specifically, and are made most practical and useful by the unique self-aligning feature described herein.

[0031]    Beyond sensing drumhead and tunable instrument vibrations, this invention has applications generally for non-contact vibration sensing of surfaces, such as, but not limited to, machine elements.

[0032]    While only certain preferred features of the invention have been illustrated and described, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.